Citation for published version:
Pan, M, Hao, Z, Yuan, C & Plummer, A 2020, 'Development and Control of Smart Pneumatic McKibben Muscles for Soft Robots', Paper presented at The 12th International Fluid Power Conference, Dresden, Germany, 9/03/20 - 11/03/20.

Publication date:
2020

Link to publication

University of Bath

Alternative formats
If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 04. May. 2023

DEVELOPMENT AND CONTROL OF SMART PNEUMATIC MCKIBBEN MUSCLES FOR SOFT ROBOTS

Min Pan*, Zhe Hao, Chenggang Yuan, Andrew Plummer

Centre for Power Transmission and Motion Control, Department of Mechanical Engineering, University of Bath, BA2 7AY, Bath, UK

* Corresponding author: Tel.: +44 1225 383023; E-mail address: m.pan@bath.ac.uk

ABSTRACT

Animals exploit soft structures to move smoothly and effectively in complex natural environments. These capabilities have inspired robotic engineers to incorporate soft actuating technologies into their designs. Developing soft muscle-like actuation technology is one of the grand challenges in the creation of soft-body robots that can move, deform their body, and modulate body stiffness. This paper presents the development of smart pneumatic McKibben muscles woven and reinforced by using conductive insulated wires to equip the muscles with an inherent sensing capability, in which the deformation of the muscles can be effectively measured by calculating the change of wire inductance. Sensing performance of a variety of weaving angles is investigated. The ideal McKibben muscle models are used for analysing muscle performance and sensing accuracy. The experimental results show that the contraction of the muscles is proportional to the measured change of inductance. This relationship is applied to a PID control system to control the contraction of smart muscles in simulation, and good control performance is achieved. The creation of smart muscles with an inherent sensing capability and a good controllability is promising for operation of future soft robots.

Keywords: McKibben muscle; Pneumatic artificial muscle; Self-sensing muscle; PID feedback control; Soft robots.

1. INTRODUCTION

The pneumatic McKibben artificial muscle was developed for artificial limb research in the 1960s [1-2]. They have been commercialized by the Bridgestone Rubber Company of Japan for robotic applications in the 1980s under the name of Rubbertuators [3]. In the 1990s, the Shadow Robot Group [4] developed the 'Digit Muscle' and in 2001 the Festo developed the 'Fluidic Muscle' [5]. The McKibben muscle is an efficient and widely used fluidic artificial muscle which consists of an elastomer inner tube and a double-helix-reinforcing-braid and can be pressurised to contract or extend. They show great advantages of flexibility, adaptability and compliant actuation compared to the conventional rigid linear cylinders. They are also remarkable for lightweight property and high energy density. The McKibben muscles have been used for many applications such as bionic arm [6] and soft manipulators [7-9]. Ideal McKibben muscle kinematic models have been developed for the field. A comprehensive survey presented the details of kinematic and static McKibben muscle models can be found in [2]. Recently, the McKibben artificial muscle started to gain more attentions as one of typical soft actuators in an emerging area of soft robotics. However, researchers are facing a variety of technical challenges in developing and understanding McKibben artificial muscles. Firstly, derived from limited strength of external fiber sleeve, McKibben actuators are still not able to survive very high operating pressure, which limits their potential applications. Secondly, the deformation of the McKibben muscle is difficult to accurately model due to its continuous and irregular shape and complex distribution of stress and friction. Thirdly, the state-of-the-art sensing technologies (e.g. conventional rigid displacement and pressure sensors) used onto McKibben muscles still have significant dimensional restrictions. This paper presents the development of smart self-sensing McKibben muscle and the design of PID control system based on the real-time self-sensing measurement. The muscle was woven and reinforced by using conductive insulated wires, in which the deformation of the muslce can be effectively measured by calculating the change of wire inductance [10-11]. The weaving angles 20˚, 30˚ and 40˚ were investigated regarding sensing and control performance. The ideal McKibben muscle models were also introduced and used for analysing muscle performance and validating sensing accuracy. The simulated results show very good control perforamnce which is promising for operation of future soft robots.

2. PREVIOUS WORK

2.1. Smart Sensing Braid

The smart sensing braid concept was proposed and introduced by Felt *et al* [10-11]. They made the reinforcing braid of a pneumatic artificial muscle (PAM) by weaving it from conductive insulated wires in order to measure the deformation of the muscle. When the muscle is pressurized and contracted, the wire inductance increases; when the muscle is extended, the wire inductance decreases. From simulated and experimental results, the muscle deformation can be effectively predicted by using a linear function of the measured inductance. This technique can be implemented without using additional embedded flexible sensors or elastomers into the muscle, which offers the advantages of easy-manufacturing and cost-efficiency.

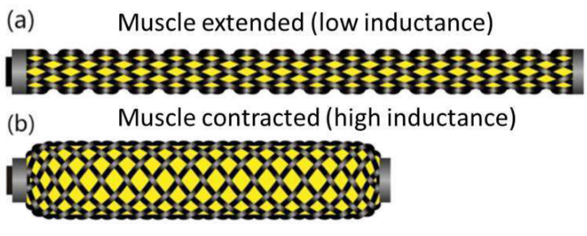

Figure 1: Smart sensing braid for measuring the deformation of a PAM

The team has also conducted some dynamic tests of the PAM for deformation measurement, which showed no phase lag and change in magnitude response for the driven frequencies up to 4 Hz. This shows that the smart braid can provide accurate measurements over a very good dynamic range for a pneumatic actuator.

2.2. Ideal McKibben Muscle Braid Model

Considering a planar network of sensing braid in a rectangular shape as shown in Figure 2, where the initial braid and contracted braid are compared in (a) and (b):

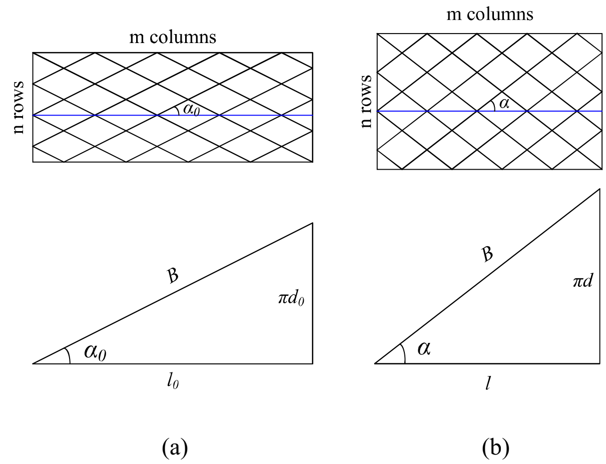

Figure 2: Geometrical characterization of the McKibben muscle braid (a) normal resting (2) pressurized

With the assumptions,

- The braid fibers are inextensible;
- The effects of the tapering at the ends of the muscle us neglected;

The initial muscle length l_0 and diameter d_0 of the braid can be written as:

$$l_0 = B\cos\alpha_0 \tag{1}$$

$$d_0 = \frac{B\sin\alpha_0}{\pi} \tag{2}$$

where B is the length of the cord and α_0 is the initial fiber angle.

The contraction ratio of the artificial muscle is:

$$\varepsilon = \frac{l_0 - l}{l_0} \tag{3}$$

where l is the contracted muscle length.
Normalized diameter and length are given by:

$$\frac{d}{d_0} = \frac{\sin\alpha}{\sin\alpha_0} \text{ and } \frac{l}{l_0} = \frac{\cos\alpha}{\cos\alpha_0} \tag{4}$$

Assuming an ideal McKibben artificial muscle is an ideal cylindrical fluidic actuator, the ideal muscle force is [2]:

$$F_{ideal}(\varepsilon) = \pi r_0^2 P[a(1-\varepsilon)^2 - b],\ 0 \le \varepsilon \le \varepsilon_{\max} \tag{5}$$

where $a = \dfrac{3}{\tan^2\alpha_0}$ and $b = \dfrac{1}{\sin^2\alpha_0}$.

The maximum force is achieved when $\varepsilon = 0$; while the maximum contraction is realized when

$F_{ideal} = 0$. Therefore, we can derive the ideal muscle

$$F_{ideal\max} = \frac{1}{4}\pi d_0^2 P(a-b) \tag{6}$$

$$\varepsilon_{ideal\max} = 1-(1/\sqrt{3}\cos\alpha_0) \tag{7}$$

$$d_{ideal\max} = \sqrt{2/3}(d_0 / \sin\alpha_0) \tag{8}$$

$$\alpha_{ideal\max} = \arctan(\sqrt{2}) \tag{9}$$

2.3. Ideal Inductance Model

The smart braid can be seen as a long solenoid and the inductance can be modelled as [10, 12]:

$$L = \mu \frac{N^2 A}{l} \tag{10}$$

where μ is the magnetic permeability of the core and N is the number of turns. A and l are the cross-sectional area and the length of the muscle.

Researchers have also used the Neumann formula for modelling the braid inductance [10], which provides better accuracy but requires more computation.

In this work, the ideal McKibben muscle braid model (6)-(9) and the inductance model (10) are used for analysing muscle performance and sensing accuracy.

3. SMART MUSCLE CONTROL

Unlike rigid actuators and robots, which are generally designed to function in well-defined environments, soft actuators and robots, are developed to adapt to more unpredictable environments with insufficient information of precise location. The open-loop control approach is effective for a variety of applications when the estimated models of the actuators are sufficiently sophisticated. For PAMs, open-loop control has been tried but is not very effective [13-15] as the current numerical muscle models are not sufficiently accurate. Closed loop control requires an accurate real-time contraction measurement, which is hard to achieve without compromising the multi-degree of freedom compliance of the muscles.

3.1. Smart Muscle Prototyping

The smart braid was used as the displacement sensor and the protective shell of the muscle to reinforce the inside muscle flexible tube. To prototype the muscles and ensure the consistence of weaving, three 3D-printed Smart Braid templates were manufactured using an Ultimaker 2+ 3D printer with weaving angles of 20°, 30°, and 40°, as shown in Figure 3. The shape of the templates was designed in CATIA and the TPU 95A printing material was used to fabricate the weaving templates. The TPU 95A provides softer and more flexible properties, compared to PLA material. The completed weaving braids can be easily removed from the TPU templates, in which has significantly improved the fabrication efficiency. The braided wire sleeve was built by weaving a single strand of flexible electrical wire over two TPU 95A soft templates. The 22 AWG ultra-flexible wire manufactured by Daburn was used to weave the templates as smart braids. The inner the wire is made up of 168 strands of soft tinned copper thread. The large number of strands makes the inductance measurement more stable and easier to measure.

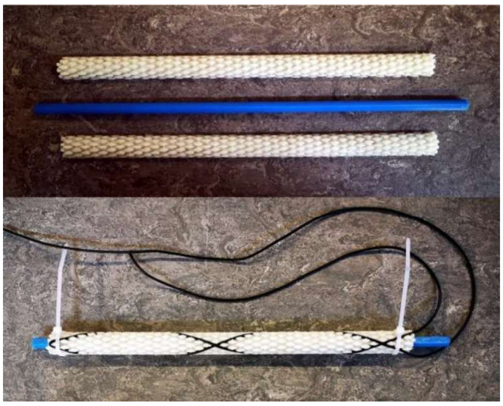

Figure 3: 3D-printed weaving templates

Three smart muscle prototypes using weaving angles of 20°, 30°, and 40° and rubber latex tubes were constructed, as shown in Figure 4. The muscle length is 250mm.

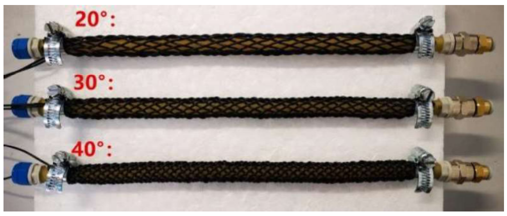

Figure 4: Smart muscle prototypes with different weaving angles

3.2. Inductance Measurement

The inductance of the smart braid was measured using a Newtons4th PSM3750 Phase Sensitive Multimeter, which provides high accuracy and superior stability. The measured real-time data was acquired and sent to the Simulink Real-Time System, as shown in **Figure 5**.

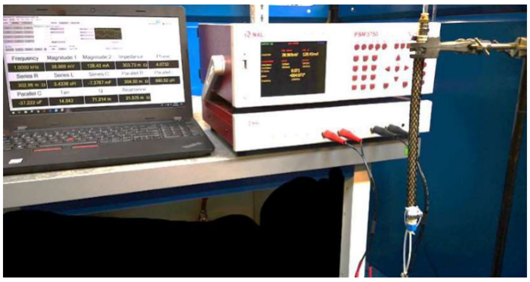

Figure 5: Inductance measurement using Newtons4thPSM3750 Phase Sensitive Multimeter

Figure 6 shows clear linear relationships of the muscle length and the measured inductance for three different weaving braids. The results show that the inductance-measurement approach is versatile and can be used for a variety of muscles with different reinforcing arrangements.

Simulink Real-Time System

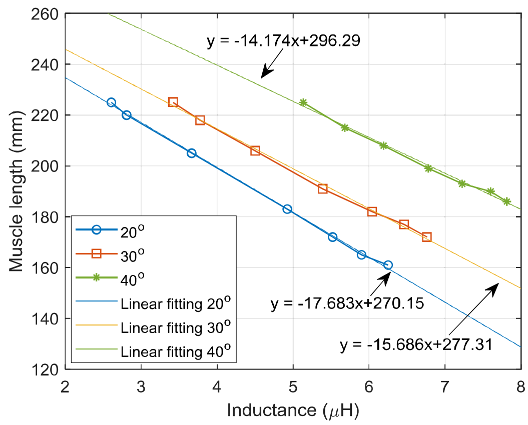

Figure 6: Relationships of the muscle length and the measured inductance for three different weaving braids

Three fitting curves were achieved based on the experimental results:

$$l(L) = \begin{cases} -17.683L + 270.15 & \alpha_0 = 20^o \\ -15.686L + 277.31 & \alpha_0 = 30^o \\ -14.174L + 296.29 & \alpha_0 = 40^o \end{cases} \quad (11)$$

where α_0 is the weaving angle, l is length in mm, and L is the inductance in μH.

3.3. PID Controller Design

Muscle dynamic response and identification

In order to design a feedback controller for the smart muscle, the muscle dynamic response was investigated firstly using the frequency analyser. Figure 7 shows the experimental setting-up of the muscle dynamic response test. A Festo proportional directional control valve MPYE-5-M5-010-B was used to control the air flow and one high-precision Festo pressure transmitter SPTW-P25R-G14-VD-M12 was used to measure the system pressure. The smart muscle with a weaving angle of 30° was tested without load. A sinusoidal pressure with a frequency of 1-4 Hz with a step of 0.25 Hz and a maximum amplitude of 2.5 bar was used to drive the smart muscle to determine the dynamic response. Figure 7 shows the schematic of the testing bench.

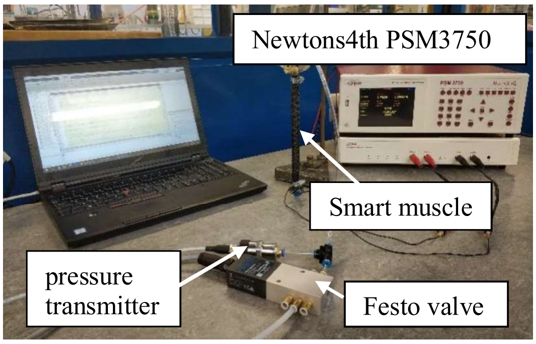

Figure 7: Schematic of muscle dynamic test

The dynamic inductance response is shown in Figure 8, where the inductance measurement responded well to 4 Hz.

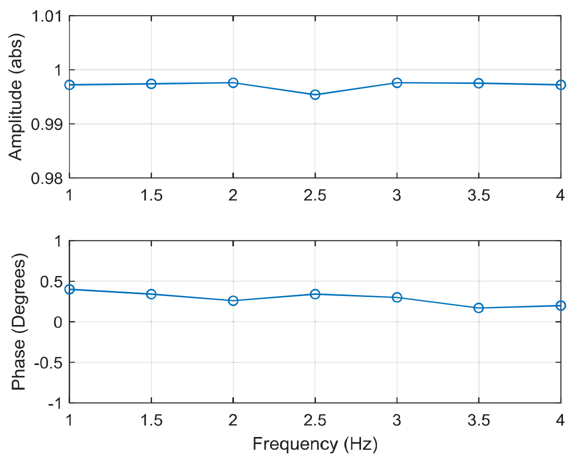

Figure 8: Dynamic inductance response of a smart muscle with a weaving angle of 30°

Simulated results

The proposed control system is shown in Figure 9, where the PID algorithm is applied to the system. The flow control valve is modelled as a second-order transfer function with a natural frequency of 115Hz [16] and a damping ratio of 0.8, given as:

$$H(s) = \frac{5.221\times10^5}{s^2 + 1156.1s + 5.221\times10^5} \qquad (12)$$

The sensing braid is used to measure the muscle length (displacement), which is feedback to the PID controller.

The muscle is modelled by using a second-order function with a natural frequency of 2Hz and a damping ratio of 0.8.

$$S(s) = \frac{12.57}{s^2 + 20.11s + 12.57} \qquad (13)$$

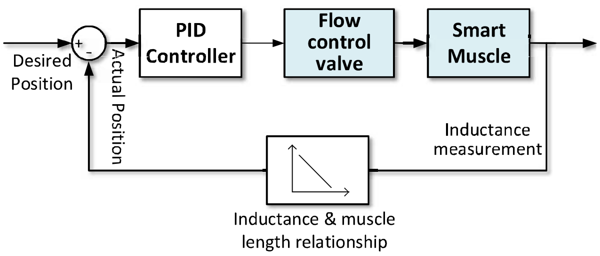

Figure 9: PID controller for smart muscles

The flow control valve was driven by the desired voltage from the PID controller. Figure 10 shows the simulated results from the feedback control system with a desired sinusoidal muscle displacement. The frequencies of the driven signal were 1 Hz and 3 Hz. The PID controller is tuned with the proportional gain of 14, the integral gain of 12.32 and the derivative gain of 0.369 to control the smart muscle operating at 1 Hz. For 3Hz, the controller is tuned with the proportional gain of 25, the integral gain of 24.55 and the derivative gain of 0.475. The results showed that the actual displacement agrees well with the desired signal. The inductance measurement of muscle deformation provides an effective means to the control of muscle.

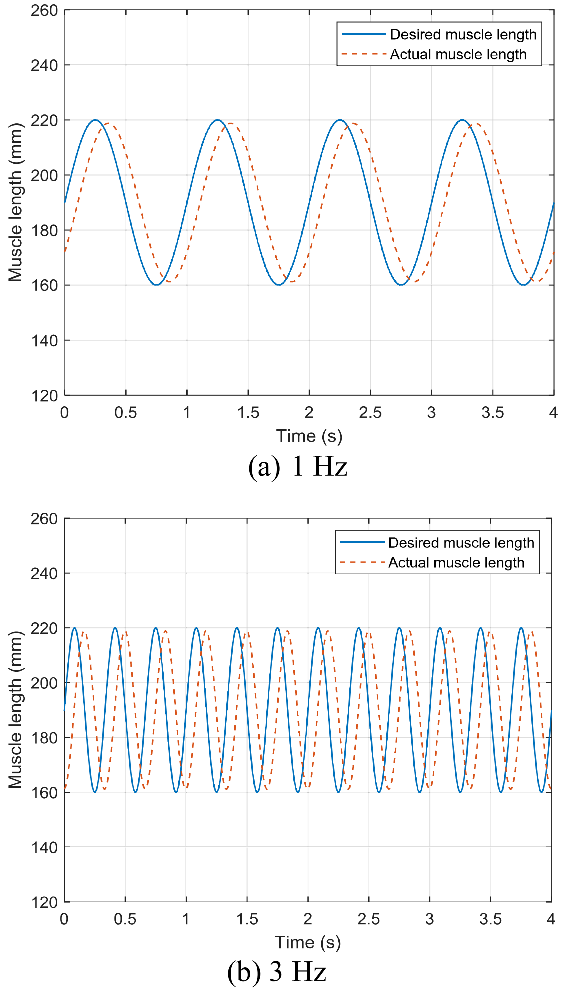

Figure 10: Simulated muscle lengths with a sinusoidal driven signal of frequencies of (a) 1 Hz (b) 3 Hz

Figure 11 shows the simulated results of the muscle length with a step driven signal of 1 Hz. The results showed that the smart muscle has a settling time within 0.5 s. When pressurized, the muscle is contracted, and its length decreased to 160 mm from 220 mm. The designed PID controller (P: 35, I: 39.24, D: 0.66) is robust and can effectively control the muscle length with the inductance sensing approach.

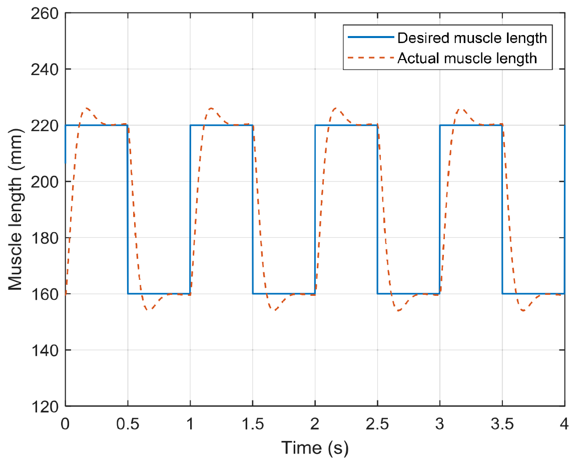

Figure 11: Simulated muscle lengths with a step driven signal of a frequency of 1 Hz

4. DISCUSSION AND CONCLUSIONS

In this work, the smart sensing braid approach proposed in [10-11] was investigated and validated through a PID feedback control system. Well-calibrated smart braid can provide rapid and precise measurements of actuator length. Different to the work in [15], the muscle prototypes used were reinforced by the smart braid directly, and a PID control system is designed with a targeted bandwidth up to 3 Hz. A second-order transfer function is used to represented muscle dynamics. The simulated results showed good control performance when the muscle was driven by the sinusoidal and step inputs. However, we believe the nonlinearity of the muscle in practice could affect control performance and the muscle dynamics could be more complicated. A simple transfer function could be insufficient to representing varying muscle deformation and dynamics. We are developing an adaptive control system to accommodate this aspect. A nonlinear PID control system can be also developed for improved control performance in practice. The smart braid has offered a very good approach to map the muscle motion. Currently the calibration curves are based on the steady-state measurement. Dynamic measurements and accurate inductance models could benefit the accuracy and performance of the control system and the understanding of muscle motion in multiple degree-of-freedom.

ACKNOWLEGEMENT

The authors would like to thank the research group at the University of Michigan sharing the ideas on https://softroboticstoolkit.com/smart-braids.

REFERENCES

[1] Artificial muscle, Life, pp. 87-88, March,1960.
[2] Tondu, B. (2012) Modelling of the McKibben artificial muscle: A review. Journal of Intelligent Material Systems and Structures, 23(3), pp.225-253.
[3] Bridgestone Corporation (1987) Rubbertuators and applications for robots, Technical Information.
[4] Greenhill, S., (1993) The digit muscle. Industrial Robot: An International Journal, 20(5), pp.29-30.
[5] Festo AG (2001) Fluidic muscle MAS. Technical document trend 11, IS 1101 www.festo.com.
[6] Tondu, B., Ippolito, S., Guiochet, J. and Daidie, A., 2005. A seven-degrees-of-freedom robot-arm driven by pneumatic artificial muscles for humanoid robots. The International Journal of Robotics Research, 24(4), pp.257-274.
[7] Thanh, T.D.C. and Ahn, K.K., 2006. Nonlinear PID control to improve the control performance of 2 axes pneumatic artificial muscle manipulator using neural network. Mechatronics, 16(9), pp.577-587.
[8] Andrikopoulos, G., Nikolakopoulos, G. and Manesis, S., 2011, June. A survey on applications of pneumatic artificial muscles. In 2011 19th IEEE Mediterranean Conference on Control & Automation (MED) (pp. 1439-1446).
[9] Li, H., Kawashima, K., Tadano, K., Ganguly, S. and Nakano, S., 2011. Achieving haptic perception in forceps' manipulator using pneumatic artificial muscle. IEEE/ASME Transactions on Mechatronics, 18(1), pp.74-85.
[10] Felt, W., Chin, K.Y. and Remy, C.D., 2015. Contraction sensing with smart braid McKibben muscles. IEEE/ASME Transactions on Mechatronics, 21(3), pp.1201-1209.

[11] Felt, W. and Remy, C.D., 2014, September. Smart braid: Air muscles that measure force and displacement. In *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems* (pp. 2821-2826). IEEE.

[12] Felt, W., Lu, S. and Remy, C.D., 2018. Modeling and design of “Smart Braid” inductance sensors for fiber-reinforced elastomeric enclosures. IEEE Sensors Journal, 18(7), pp.2827-2835.

[13] Nakamura, T. and Shinohara, H., 2007, April. Position and force control based on mathematical models of pneumatic artificial muscles reinforced by straight glass fibers. In Proceedings 2007 IEEE International Conference on Robotics and Automation (pp. 4361-4366).

[14] Hao, L., Yang, H., Sun, Z., Xiang, C. and Xue, B., 2017. Modeling and compensation control of asymmetric hysteresis in a pneumatic artificial muscle. Journal of Intelligent Material Systems and Structures, 28(19), pp.2769-2780.

[15] Felt, W., Chin, K.Y. and Remy, C.D., 2017. Smart braid feedback for the closed-loop control of soft robotic systems. Soft robotics, 4(3), pp.261-273.

[16] FESTO Proportional Directional Control Valves MPYE